Near-Bottom Turbulence and Sediment Resuspension Induced by Nonlinear Internal Waves

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LONG-TERM GOALS

The long term goal of this work is to develop a fundamental understanding and predictive capability of the underlying physics of the interaction of nonlinear internal waves (NLIWs) with the continental shelf seafloor over a broad range of environmental conditions. We are particularly interested in how such interactions impact underwater optics and acoustics and shelf energetics and ecology by stimulating enhanced bottom boundary layer (BBL) turbulence and particulate resuspension leading to benthic nepheloid layer (BNL) formation.

OBJECTIVES

The specific objectives are:

- Using Large Eddy Simulations (LES), investigate the structural transition to turbulence within the separated BBL layer under a NLIW of depression and quantify the resulting NLIW energy losses.
- By means of Lagrangian coherent structure (LCS) theory, identify mechanisms for the capturing of nearbed particles by the BBL-turbulence and their transport/deposition into BNLs.
- Analyze field observations from the New Jersey shelf to identify the applicability of hypothesized BBL physics and flesh out the underlying fluid mechanics from the field data.

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APPROACH

Our approach relies on implicit 3-D Large Eddy Simulation (LES) based on spectral multidomain solvers developed by P.I. Diamessis group. In the original stages of this project, i.e. its first five months (8/15/11 to 1/15/12) , our efforts used a recently developed spectral quadrilateral multidomain penalty method (SMPM) Navier-Stokes solver developed by a recently graduated PhD student in the P.I.'s group. The primary advantage of this code is the existence of a Legendre-polynomial-based spectral multidomain penalty discretization in the along-wave direction. By virtue of such a discretization, one can flexibly adjust the resolution along the wave, namely by focusing in the most active regions of the NLIW-driven BBL, while still maintaining high accuracy and minimum artificial dissipation.

The numerical underpinnings and validation of the new code are documented into two recently completed computationally-oriented articles (Escobar-Vargas et al. 2011a, Escobar-Vargas et al. 2011b). A sizable fraction of the latter paper describes application of this new code to a number of test cases, which also involves work done by the postdoc supported by this grant. Specifically, a NLIW in a two-layer stratification,computed from the solution of the Dubreil-Jacotin-Long equations (Dunphy et al. 2011), was inserted as an initial condition in a domain with free-slip top/bottom boundary conditions. The NLIW then propagated freely for 20 wavelengths. The numerically simulated NLIW was able to successfully maintain its form (amplitude and wavelength) and theoretically computed phase speed with minimum numerical dispersion and dissipation. Lower-order accuracy codes are challenged in producing such a robust response (Vitousek and Fringer 2011).

However, when transitioning to using our new code for the study of NLIW-induced BBLs we ran into unexpected issues of reduced numerical efficiency. Specifically, non-hydrostatic simulations of NLIWs are plagued by significant slowdown of the associated pressure Poisson equation (PPE) solver due to the elevated lepticity of the grid, i.e. its high aspect ratio, where the along-wave dimension of a grid-cell its much larger than its vertical one (Scotti and Mitran 2008) and the conditioning of the Poisson matrix becomes significantly suspect. The above aspect ratio becomes dramatically high when requiring very fine vertical resolution of the NLIW-induced BBL. As a result, preliminary 2-D simulations that we ran showed a six-to-eight-fold increase in PPE solution cost, with respect to more standard test cases (e.g. stratified lock exchange). In some occasions, numerical noise, linked to the above precarious conditioning, appeared at the subdomain interfaces.

Resolution of the above numerical issues would require significant refinement of the PPE solution algorithm (Santilli and Scotti 2011), which is outside of the scope of this project. Consequently, we decided to switch back to the pre-existing code of the P.I. (Diamessis et al. 2005), which has been tested for a number of environmentally stratified flow process simulations, including 2-D simulations of NLIW-induced BBLs (Diamessis and Redekopp 2006, Sakai et al. 2012). This older code employs a uniform periodic (Fourier-based) grid in the along-wave direction. With such a grid, adequate resolution of the active regions of the 3-D NLIW-induced BBL necessitates use of a large number of points in the along-wave direction of $O(8 \times 10^3)$. Nonetheless, the older code does not experience the same challenges in the solution of the PPE that its newer counterpart does and, thus, is a lot more efficient when applied to the problems of interest, especially when run in parallel, as is the case of simulating 3-D NLIW-induced BBLs.

Our problem geometry considers a mode-1 wave of *depression* fixed in a frame of reference moving with the NLIW through a uniform-depth waveguide (figure 1). The background stratification acrposs the full water column consists of a two uniform density layers separated by a finite-thickness pycnocline (figure 1). As the wave is kept fixed in time, we solve for the perturbation to this wavefield that develops through the mismatch between the non-zero wave velocity field and no-slip condition at the bed (Diamessis and Redekopp 2006). To maximize resolution of the 3-D turbulence in the NLIW-induced BBL, our computational domain is a truncated in the vertical direction. A detailed view of the computational domain with the apropriate boundary conditions and a sample grid is shown in Figure 1.

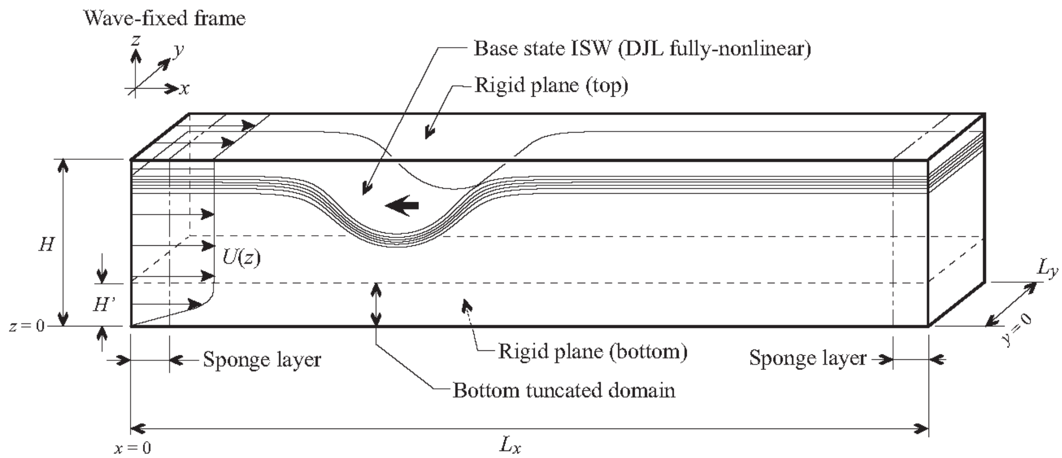

Figure 1: Basic setup for numerical simulations. Enabled by the use of a "fixed" (time-independent) NLIW, the three-dimensional bottom boundary layer simulations are performed in a bottom-focused domain. This bottom domain has a height which is typically 25% the total water column depth. The frame of reference is fixed to the wave, which propagates against a weak barotropic current with its own boundary layer.

Finally, our particle-tracking tools revolve around libraries built by co-P.I. Jacobs based on a higher-order accuracy Eulerian-Lagrangian (EL) approach (Jacobs and Hesthaven 2006, Jacobs and Don 2009). These tools, based on a parallel, high-order accurate EL approach on multi-block, spectral and fully unstructured grids, have been used by the co-P.I. to determine particle-laden flow with relevance to liquid-fuel combustors . Originally developed for a discontinuous Galerkin-based flow solver for the compressible Navier-Stokes equations, these tools are directly compatible and implementable within the incompressible spectral multidomain method that the P.I. has developed. Relevant implementation will be performed in early Spring 2013.

WORK COMPLETED

As indicated in the previous section, the first five months of this project were dedicated by the postdoc towards implementing a fully nonlinear internal wave (DJL-solution-based) into our newer quadrilateral subdomain code, testing the waves robust during propagation over long distances and performing prelminary simulations of the NLIW-induced BBL. The first-step following our switch to the pre-existing parallel code, which employs a Fourier discretization, was to adapt the older code to study the particular problem at hand. The NLIW was introduced as a fixed wave and sponge layers were added to the streamwise boundaries ; the latter prevents any re-entry of vortices shed by the NLIW-induced near-bed wake from the periodic streamwise boundary thereby allowing long-time simulations of the BBL. In addition, a dealiasing scheme (Kopriva 2009) was implemented in the multidomain-discretized vertical direction to further buttress it against numerical instability and allow for as high a Reynolds number as possible at minimal computational cost. Finally, a synthetic 3-D noise generator, originally designed by the co-P.I., was incorporated in our numerical solver. Such physically-designed synthetic noise is a commonly used tool in turbulent boundary layer simulations. In our problem, use of this noise generator critical for the rapid development of 3-D perturbations in the simulated NLIW-induced BBL.

Prior to transitioning to 3-D simulations, a number of preliminary 2-D simulations were performed to establish the reliability and robustness of our fundamental flow configuration shown in figure 1. To this end, note that, in all simulations so far, we include a model background barotropic current with its own idealized boundary layer structure. The results of these 2-D simulations have been incorporated in a previously submitted article , currently under revision (Sakai et al., 2012), which supplements a recently published article, co-authored by the P.I., on the criterion for near-bed vortex wake formation under NLIWs as a function of quantities measurable by ADCPs and thermistor arrays in the field (Aghsaee et al. 2012). Now, the presence of such a background current is necessary for near-bed vortex-shedding to develop, at least in the framework of a 2-D simulation. Note that laboratory studies at comparable wave-based Reynolds numbers do show the formation of near-bed shed vortices in the absence of a background current, an issuewe plan to investigate in our 3-D production runs.

Finally, in the framework of 2-D simulations, we have additionally tested the response of the NLIW-induced BBL t tohe externally superimposed background, artificial noise (Sakai et al. 2012). This particular investigation provides guidelines towards enhanced efficiency in the generation of bottom turbulence in the 3-D runs. Moreover, it bears implications for the role of background boundary layer turbulence in the ocean and its impact on turbulence in the NLIW footprint.

Having performed these critically necessary 2-D investigation, we began conducting 3-D simulations in August 2012. All 3-D runs are performed using the computing resources of DoD HPCMP Open Research Systems. We are currently using the baseline case shown in figures 2 and 3, with a weak barotropic current of magnitude $U_0=0.1c$. A typical 3-D simulation requires a resolution of 8192 × 64 × 300 points and is run in parallel on 64 processors with a wall-clock time of 2 to 3 weeks.

We first ran in 3-D without adding any external noise but the result was essentially 2-D. No 3-D flow structure was observed even after vortex shedding was initiated. The formation of any 3-D flow in the wave-induced requires the insertion of some noise in the form of synthetic turbulence once the 2-D BBL has formed under the wave. Sample results are given in the next section.

RESULTS

Figure 2 shows the effects of background current magnitude on the formation of a separation bubble and vortex shedding patterns in the wave-generated BBL. The near-bed shear instability is enhanced as the current magnitude becomes larger.

Figure 3 shows an example from a 2-D simulation of the response of the NLIW-induced BBL to externally imposed noise in the presence of a weak background barotropic current is used with a magnitude of U_0=0.1c ; here c is the wave phase speed. In the absence of any external noise, either the wave amplitude or the current strength need to be increased, for a BBL shear instability to develop and a near-bed vortex wake to be initiated. The insertion of external noise not only triggers a near-bed vortex wake (visible by the long packet of vortices growing downstream of the wave center) at lower wave amplitudes and weaker background current amplitudes, it also drives a much more rapid development of the instability. This finding is critical for reducing the computational cost of the 3-D simulations. From an actual oceanic BBL standpoint, we can regard this combination of a barotropic current (and its associated boundary layer) with the external noise as a surrogate for the the typically turbulent BBL that lies ahead of the propagating NLIW. This ambient turbulent BBL can excite the bottom boundary shear flow generated by the wave in such a way that it triggers a near-bed instability and vortex wake which have a distinct signature in the form of fluctuating, large vertical velocities, and potentially sediment resuspension in, the footprint of a propagating NLIW.

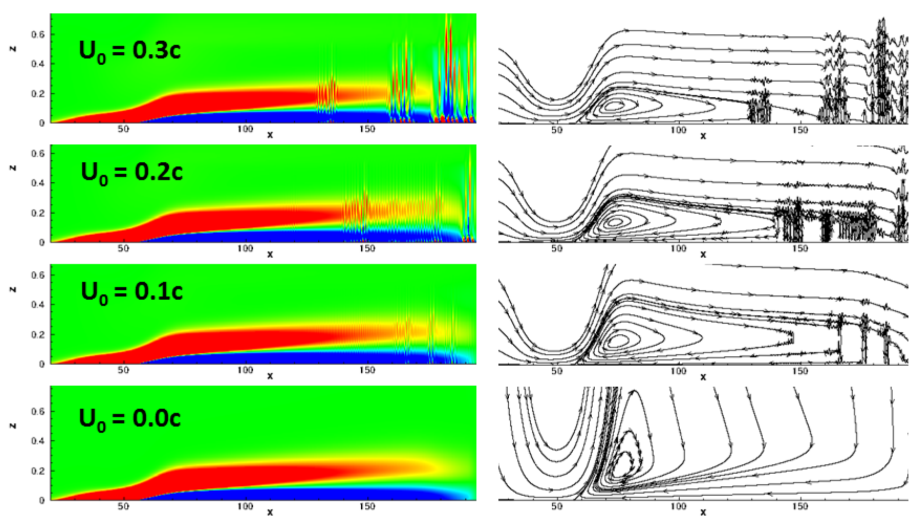

***Figure 2: Snapshots of perturbation vorticity (left column) and instantaneous streamlines (right column) for different background current amplitudes U_0={0.3c, 0.2c, 0.1c, 0.0c} where c is the wave phase speed. All the snapshots are taken at non-dimensional time tc/H=15.2. The base state NLIW has amplitude of 0.346H and the wave Reynolds number is for all cases. In the snapshots shown, the water column has a depth of H*=10m *and the domain is* 400m *long, with the center of the wave located at x=0*m.**

Figure 4 shows several snapshots of the development of the NLIW-induced BBL in an exploratory 3-D simulation at the same parameter values as those shown in figure 3. In the absence of any noise, a laminar NLIW-induced BBL emerges without any near-bed vortex wake. When adding the noise, a shear instability similar to that observed in 2-D simulations occurs in the form of laterally coherent near vortices that ascend into the water column. Nevertheless, these vortices quickly develop a 3-D structure and eventually break-down into BBL turbulence. Effectively, a near-bed turbulent wake forms that persists considerable distance downstream of the wave trough. Quite curiously, presumably due to dissipation of the turbulence, a 2-D vortical structure is recovered sufficiently far from the wake trough. To the best of our knowledge, no such observations have been previously reported in the literature.

At the time of writing this report, tests ensuring grid-independence and the appropriate domain width are nearing their completion. We have additionally checked the adequacy of our resolution against commonly used criteria in the separated BBL literature in the aerodynamics community. For the Reynolds numbers shown in figures 2 to 3, our resolution is such that our simulations are very close to a Direct Numerical Simulation (DNS). No subgrid-scale model will thus be used in our production runs.

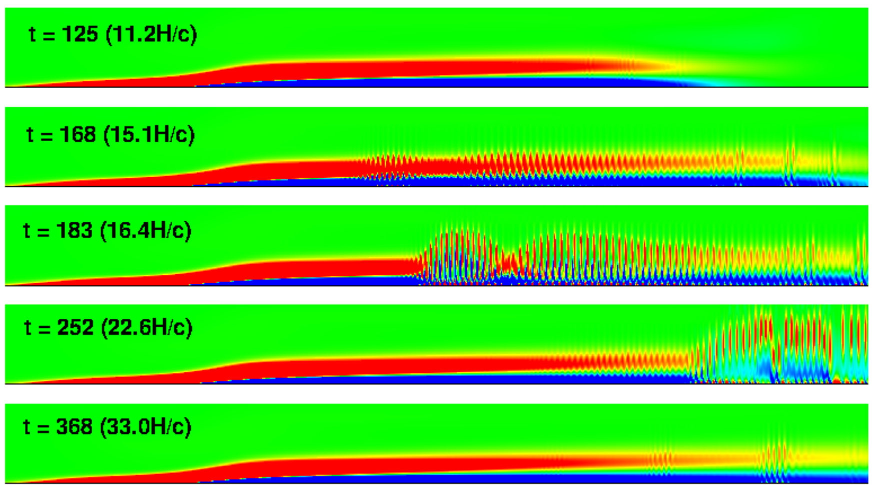

Figure 3: Response of BBL vorticity field to background noise superimposed instantaneously at t=125 (see snapshots for non-dimensional times). The background current has a magnitude of 0.1c, where c is the NLIW phase speed. The superimposed velocity noise field has maximum amplitude of 0.1% of the NLIW phase speed. The base state NLIW has amplitude of 0.346H and the wave Reynolds number is $Re_W = cH/\nu = 1.6\times10^5$***, where H is the water column depth.***

The 3-D production runs will begin in mid-to-late November. We will perform a total of six 3-D simulations which will combine two different stratifications (shallower vs. deeper thermocline), two wave amplitudes and two Reynolds numbers. An additional run, for the case of most vigorous BBL turbulence, will be performed in the absence of a weak background current. Given constraints of memory and numerical stability and our preference to examine BBL physics unaffected by a subgrid scale model, we will limit ourselves to a maximum wave-based Reynolds number of 3×10^5. This value is a factor of 3 larger than those considered in the laboratory experiments of Carr et al. (2008). Although the DNS Reynolds number is two-to-three orders of magnitude smaller than what is encountered in the ocean, significant novel insights are expected to be gained with respect to NLIW-induced BBL physics.

Results from the production runs will be analyzed to understand in detail the structural transition of BBL vorticity from 2-D to 3-D and its impact on bed shear-stress and pressure fields. The outstanding question of whether the formation of any near-bed wake in the absence of a background barotropic current requires a 3-D environment, i.e. whether the initial instability leading to the wake is actually 3-D in nature, will be answered. Additionally, we will determine whether the intermittent benthic eruptions of packets of shed vortices observed in 2-D runs (Sakai et al. 2012) actually occur in 3-D, as implied by similar studies in aerodynamics. The bottom drag under the wave will be computed and parameterized as a function of measurable NLIW characteristics. Finally, measurements from virtual ADV probes positioned in the wave-path will be obtained to provide characteristic signatures of NLIW-induced BBL turbulence identifiable in field measurements.

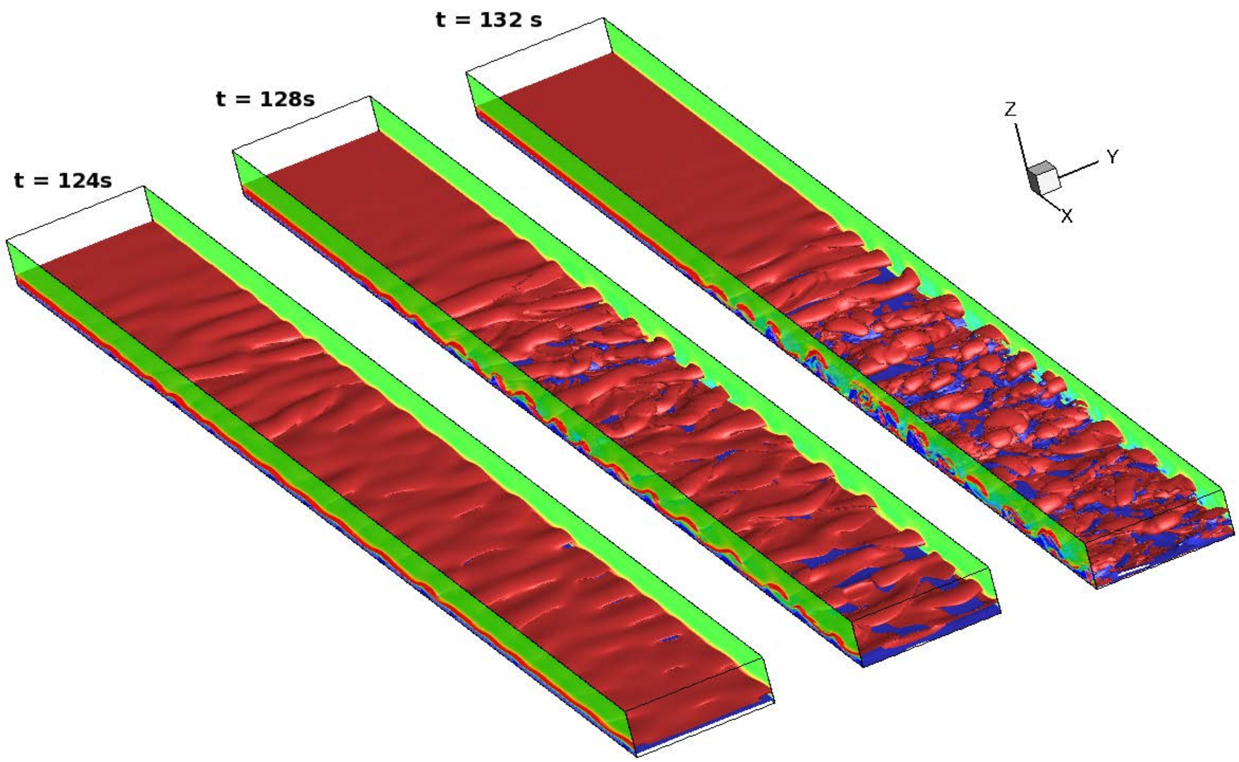

Figure 4: Evolution to three-dimensional BBL turbulence under the NLIW of figure 3. Shown are spanwise vorticity isosurfaces in a streamwise-truncated section of the computational domain, focused on the rear of the NLIW where turbulence is most active (the left end of the domain corresponds to the wave trough). A synthetic turbulent velocity noise field with amplitude of 0.1% of the NLIW phase speed is instantaneously superimposed on the initially laminar 2-D NLIW-induced BBL at time tc/H=8. The first (left-most) snapshot is taken at tc/H=10.2. The two subsequent snapshots are chronologically separated by tc/H=0.36. Note that the simulation is conducted in the bottom 25% of full domain.

IMPACT/APPLICATIONS

The accurate representation of the structure and magnitude of shear stress field field in the NLIW footprint and accurate estimation of the NLIW energy losses due to bottom interactions will allow the formulation of improved subgrid-scale parameterizations of energy dissipation and bottom boundary conditions for larger-scale operational forecasting models used to simulate environments with high NLIW activity. An enhanced understanding of the underlying physics of the NLIW-driven BBL also provides critical insight on how the bottom shear stress and pressure fields conspire to generate high-amplitude sandwaves, such as those observed in the South China Sea, which can pose significant challenges in efforts of acoustic bathymetry mapping. Finally, the generated resuspended particle distributions under NLIWs, a reliable proxy of BNLs, can be used to quantify the transmission or backscatter of optical/acoustic signals of importance to remote sensing efforts and near-bed SONAR operation.

RELATED PROJECTS

Funded, by an NSF-CAREER award in Physical Oceanography, the P.I. is using the quadrilateral SMPM code, originally used in this project, to study the shoaling of NLIWs in both canonical configurations and domains with bathymetry replicating the South China Sea (SCS). The physical phenomenon of interest is the formation of trapped cores in shoaling waves which involve comparison with field data from Dr. Ren-Chieh Lien of APL-U. Washington obtained in the SCS region. A Ph.D. student is working on implementing deformed spectral subdomains in the SMPM code necessary for the simulation of shoaling bathymetries and is working on improving the efficiency of the quadrilateral multidomain code. Supported by the CAREER award and a code 33 O.N.R. grant, the P.I. is currently writing an article on the nonlinear generation of harmonics during the impact of an internal wave beam on a model sharp oceanic pycnocline and the associated interfacial wave generation. The particular effort involves a collaboration with Dr. Scott Wunsch of the Applied Physics Lab at Johns Hopkins University. The associated simulations and data analysis for were performed by an undergraduate student. Finally, the P.I. is serving as a co-P.I. with Prof. Phil Liu (Civil and Env. Eng., Cornell) in a project where a PhD student is examining the development of a BBL over rippled bathymetries in the passage of a surface solitary wave.

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<u>*Submitted*</u>:

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